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Rotational Velocities of Very Low Mass Binaries

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Abstract. We present rotational velocities for individual components of eleven very low mass (VLM) binaries with spectral types between M7.5 and L4. These results are based on observations taken with the near-infrared spectrograph, NIRSPEC, and the Keck II laser guide star adaptive optics (LGS AO) system. The binaries were targeted as part of a dynamical mass program, and their orbital inclinations are used to translate $v\sin i$ into a rotational velocity for each component. We find that the observed sources tend to be rapid rotators ($v\sin i > 10$ km s^{-1}), consistent with previous measurements for ultracool objects. Five systems have component $v\sin i$'s that are statistically different, with three binaries having velocity differences greater than 25 km s^{-1}. To bring these discrepant rotational velocities into agreement would require their rotational axes to be inclined between 10 to 40^{o} with respect to each other, and that at least one component has a significant inclination with respect to the orbital plane. Alternatively, each component could be rotating at a different rate, even though they have similar spectral types. Both differing rotational velocities and inclinations have interesting implications for binary star formation. Two of the binaries with large differences in rotational velocity are also known radio sources, LP 349-25AB and 2MASS 0746+20AB. LP 349-25B is rotating at $\sim$95 km s^{-1}, within a factor of $\sim$3 of the break up speed, and is one of the most rapidly rotating VLM objects known.

1. Introduction

Rotational velocity is an important diagnostic parameter for stellar objects, offering a window into the angular momentum evolution of a given source. Measurements of rotational velocity have been shown to correlate strongly with stellar activity, possibly driving the magnetic dynamo responsible for generating this activity (Browning 2008).

In addition, rotational velocities have been shown to correlate with the age of a system, offering a tool for estimating stellar ages (Delfosse et al. 1998).

The rotational behavior of very low mass stars and brown dwarfs has been studied by a number of authors in recent years (Mohanty & Basri 2003; Bailer-Jones 2004; Zapatero Osorio et al. 2006; Reiners & Basri 2008, 2010). It has been shown that the brown dwarfs tend to be rapid rotators, and that the minimum rotation rate is a function of spectral type (i.e., Zapatero Osorio et al. 2006; Reiners & Basri 2008). It has also been determined that the rotational velocities of brown dwarfs correlate with age and that their rotational evolution is probably dominated primarily by magnetic braking (Reiners & Basri 2008). However, it appears that the activity-rotation relationship that is very strong amongst M dwarfs tends to break down at these low masses (Mohanty & Basri 2003).

The majority of previous studies have been performed with seeing-limited observations, and most sources targeted are thought to be single. Known binaries have been included in various samples, and the rotational velocities derived for these objects have been from the combined light of both components. The rotational velocities of individual binary components can potentially provide a unique look at the rotational evolution of VLM objects. If the rotational velocities differ substantially from those of single objects, it could imply that VLM binaries evolve differently than single systems. Additionally, if any differences are seen between the velocities of the binary components, it could have implications for the way in which these binaries formed and their early accretion history. Finally, if the orbits of these binaries are known, it allows for the translation of projected rotational velocity into the true rotational velocity via the assumption that the rotation axis is perpendicular to the orbital plane.

We present here rotational velocity measurements for the components of a sample of tight, visual VLM binaries. The measurements of these spatially-resolved velocities are enabled by the W.M. Keck Observatory laser guide star adaptive optics (LGS AO) system, which provides high spatial resolution observations of optically faint targets (Wizinowich et al. 2006). This study is the first to examine systematically the rotational velocities of individual VLM objects that reside in binary systems.

2. Sample and Observations

2.1. Sample

Our sample is comprised of eleven VLM binaries that were targeted as part of an ongoing program to measure their dynamical masses. These objects have been observed both astrometrically and spectroscopically since 2006, and initial estimates of their orbital properties have been obtained (Konopacky et al. 2010). Their spectral types range from M7.5 to L4, and their separations range from $0\farcs07$ to $0\farcs35$. Because we are able to spatially resolve the components before obtaining high resolution spectroscopy (see section 2), our total sample consists of 22 VLM objects.

2.2. Observations

The eleven binaries were observed using the NIR spectrograph NIRSPEC (McLean et al. 2000) on Keck II 10 m in conjunction with the facility LGS AO system (NIRSPAO). These observations, taken between 2006 December and 2010 June, are described in detail in Konopacky et al. (2010). Briefly, we used the instrument in its high spectral resolution mode, selecting a slit 0.″041 in width and 2.″26 in length in AO mode. We observed in the K band in order to obtain data in the CO bandhead region (2.291 - 2.325 μm, dispersion order 33). Due to the dense population of lines in this region, our analysis for this work was done only in order 33, although the cross-dispersed data ranged from 2.044 - 2.382 μm.

A rotation was applied so that both components of each binary fell simultaneously on the high-resolution slit, which is at an angle of 105.9^o with respect to north. Typical observations consisted of four spectra of both components, each with 1200 second integration times, taken in an ABBA dither pattern along the length of the slit. Each target observation was accompanied by the observation of a nearby A0V star to measure the telluric absorption in the target spectra.

3. Analysis

Data reduction of our NIRSPAO data was performed as described in Konopacky et al. (2010). The basic reduction was done with REDSPEC, a software package designed for NIRSPEC[1]. As these systems are fairly tight binaries, cross-contamination can be an issue when extracting the spectra. We therefore use a Gaussian extraction method, fitting each spectral trace with a Gaussian of variable FWHM. In this way, one binary component's trace can be subtracted from a given frame before the other component's is extracted, minimizing contamination (Konopacky et al. 2010). The average signal-to-noise ratio of our individual spectra is ~50.

It has been demonstrated the CO bandhead line widths in order 33 are primarily a function of temperature and the projected rotational velocity ($v\sin i$) for VLM objects, with an additional moderate dependence on surface gravity (Blake et al. 2007). With some knowledge of the temperature of a given object and an allowance for varying surface gravity, $v\sin i$ measurements can be estimated from our extracted spectra. An example of the impact of $v\sin i$ on spectral morphology of the CO bandhead is shown in Figure 1. These three sources, which have roughly the same spectral type, look quite different spectrally due to their different rotational velocities.

Our extracted spectra are not corrected for telluric absorption because these features not only provide a stable reference for absolute wavelength calibration, but also provide a means of estimating the instrumental PSF. We therefore model each spectrum as a combination of a KPNO/FTS telluric spectrum (Livingston & Wallace 1991) and a synthetically generated spectrum derived from the PHOENIX atmosphere models (Hauschildt et al. 1999). The model spectrum is parameterized to account for the wavelength solution, continuum normalization, instrumental profile (assumed to be Gaussian), $v\sin i$, and radial velocity. To accurately estimate $v\sin i$, the instrumental PSF is measured on our A0V calibrator stars, which by design are a clean measure of the actual telluric spectrum. We hold the instrumental profile fixed while fitting our actual VLM spectra. The best-fit model is determined by minimizing the variance-weighted reduced χ^2 of the difference between the model and the extracted spectrum, once this difference has been Fourier filtered to remove the fringing present in NIRSPEC K-band spectra (J. Bailey, in prep). This model therefore provides our $v\sin i$ estimates.

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[1] http://www2.keck.hawaii.edu/inst/nirspec/redspec/index.html

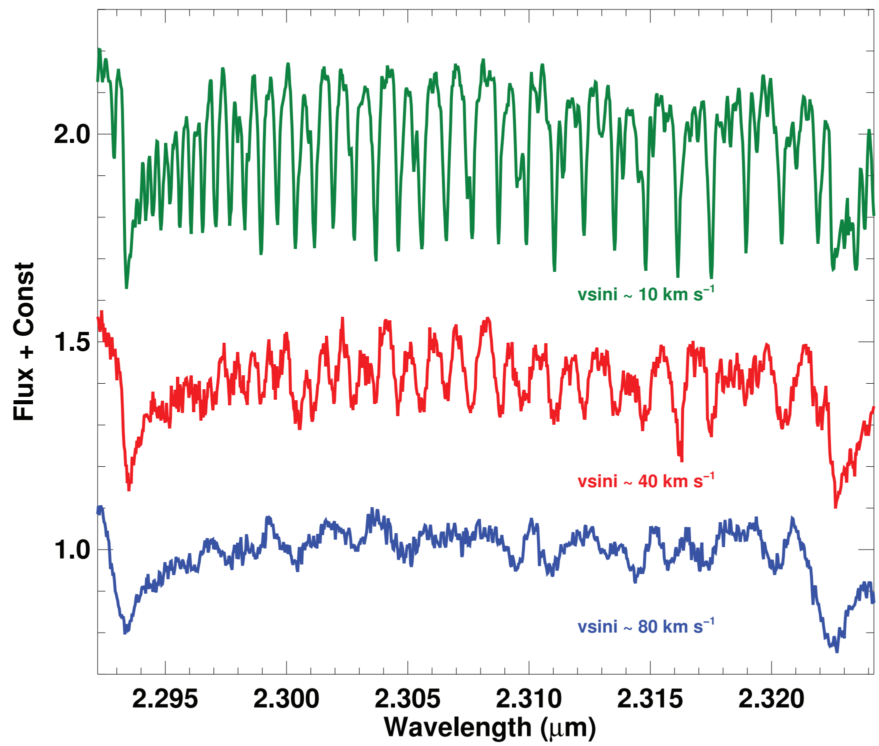

Figure 1. Three extracted and telluric corrected spectra from our sample. These spectra are from NIRSPAO dispersion order 33, and show strong CO features. All sources shown in this figure have a spectra type of ~M8, but have widely different morphologies due to varying *v*sin*i*. The measured *v*sin*i*'s for each source are given for reference.

The PHOENIX templates are generated at a fixed temperature and surface gravity. Our primary templates for each source have a temperature as measured in Konopacky et al. (2010) and a log(g) of 5.0. Statistical uncertainties are assigned by fitting each individual spectrum separately and taking the RMS of the values derived for each case. We also need to account for systematic uncertainties due to both the temperature and surface gravity dependence of our spectra. We fit each spectrum with templates spanning ±100 K in temperature and ranging from 3.0 - 4.5 dex in log(g). We then use the spread in these values around our best-fit value as our systematic uncertainty, and add these in quadrature with our statistical uncertainties.

We also estimate the lowest measureable value of *v*sin*i* in our spectra. To do this, we took our PHOENIX templates and broadened them first to the correct instrumental PSF and then to different values of *v*sin*i*. We fit these spectra using the methodology described above. We find that the limiting value for which we could accurately measure *v*sin*i* is 3 km s^{-1}.

4. Results and Discussion

We average the measured $v\sin i$'s for each source across all epochs of data. The final uncertainty for each source is the error on the mean. The measured $v\sin i$'s for all sources are above the 3 km s^{-1} limit. Our typical uncertainties are of order 10%. We plot all of our values on the left panel of Figure 2 as a function of spectral type. Also included on this plot are values for other VLM sources from previous surveys (Mohanty & Basri 2003; Reiners & Basri 2008, 2010). It is apparent that our values are consistent with previous results. Our sources tend to be relatively rapid rotators, with 17 sources having $v\sin i > 10$ km s^{-1}. This implies that the rotational evolution of objects in binary systems is not drastically different than that of single VLM objects.

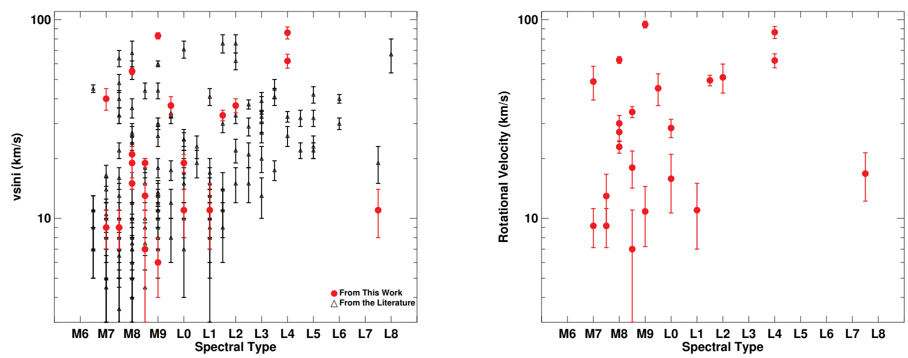

Figure 2. **Left**: Projected rotational velocity ($v\sin i$) versus spectral type for each of the binary components in our sample (red circles). Also plotted (open triangles) are previously measured values (seeing limited observations, so binaries are not resolved) of $v\sin i$ for VLM objects in the literature (Mohanty & Basri 2003; Reiners & Basri 2008, 2010). The values we measure for our sources are consistent with other VLM objects, with our sources tending towards rapid rotation. **Right**: True rotational velocities for our sources, assuming that the equatorial and orbital planes are aligned. Several of our sources are among the most rapidly rotating VLM objects yet observed.

Because these binary systems have been monitored in order to obtain their orbital solutions, the inclination of the orbital planes are measured for all sources (Konopacky et al. 2010). If we make the assumption that the inclination of the orbital plane is the same as the equatorial inclination of each source (meaning that the rotation axis is perpendicular to the orbital plane), we can turn our measured *projected* rotational velocities into *true* rotational velocities. The result of this deprojection is shown in the right panel of Figure 2.

We also examined whether the binary components have similar rotational velocities. Figure 3 shows the velocity of the secondary component of each binary plotted against that of the primary. It is immediately apparent that five sources in our sample have statistically different rotational velocities under the assumption that rotation axis is perpendicular to the orbital plane. In the case of three sources, the differences in velocity are >25 km s^{-1}. In most cases, it is the secondary component that is rotating more rapidly, although in one case the primary is rotating more rapidly.

There are two possible scenarios that could explain the results shown in Figure 3. The first is that our assumption that the equatorial planes of both components align with

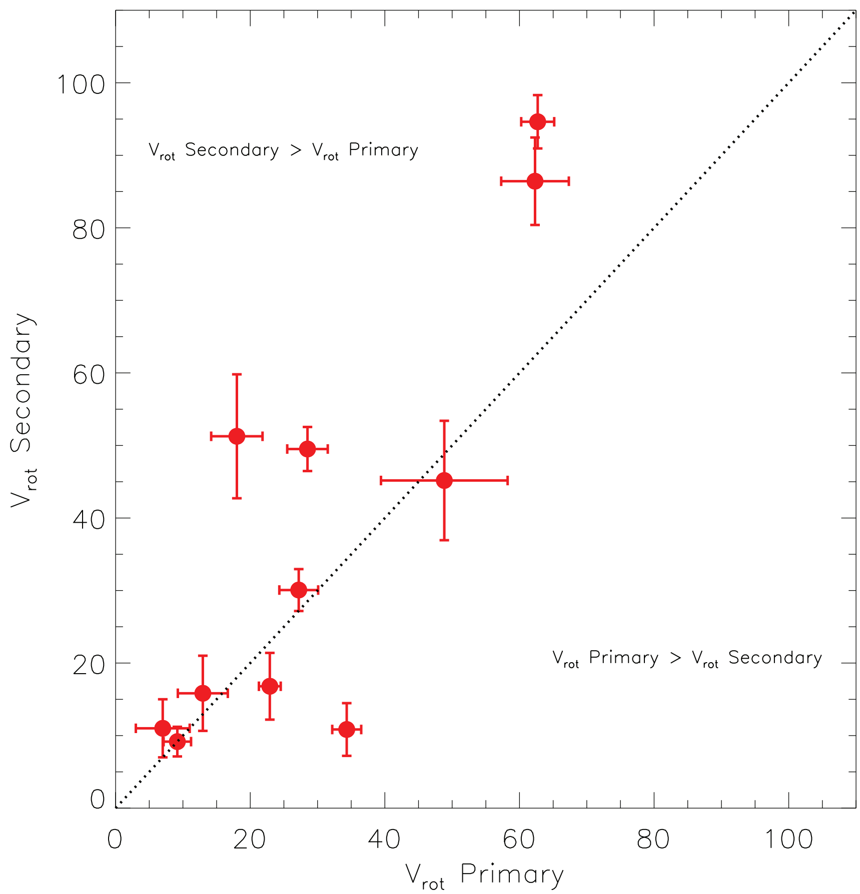

Figure 3. The rotational velocities of each secondary component plotted against its primary. Sources with consistent velocities should fall on the dotted line. Five of our eleven systems show components with different velocities, with three of these having differences >25 km s^{-1}

the orbital plane is incorrect. If one or both components is tilted with respect to the orbital plane, they could have the same true rotational velocity. All of the binaries in our sample have semimajor axes between 1 AU and 80 AU, beyond the separation regime where tidal circularization is expected. However, given the results of Hale (1994), one might expect binaries to have aligned equatorial and orbital planes, as substantial misalignment tends not to be observed for sources with separations $\lesssim$100 AU. Additional work on T Tauri binary systems have shown both slight and substantial planar misalignment via observations of disk orientation (Jensen et al. 2004; Monin et al. 2006), with the relative inclinations often of order 20^o or less. To bring the rotational velocities our sources into agreement would require a differential inclination of 10 - 40^o, consistent with these previous measurements. However, the T Tauri binaries have wider separations (>70 AU) than most of our systems, and also generally higher masses. In spite of this, the implication of such a result could be a consistent mode of formation between the higher mass and VLM systems. Turbulent core fragmentation theories of binary formation predict random component orientations (Bate 2000), whereas theories in which binaries form via gravitational instability in a disk predict rotational alignment (Bonnell & Bate 1994). In addition, interactions of components in multibody systems could produce misaligned axes. At least two of the objects in our sample with differing velocities are part of known triple systems with wide, higher mass components.

The other scenario is that the two components truly have different rotational velocities. One might basically expect binary components to have similar velocities if they formed out of the same cloud of material, with the cloud imprinting its angular momentum on the binary. However, differing component velocities have been observed in the case of the very young eclipsing binary brown dwarf, 2MASS0535-05AB (Gómez Maqueo Chew et al. 2009), making this a plausible scenario for the binaries observed in this study. A difference in rotational evolution could potentially come after initial formation, due to different amounts of accretion onto each component. In addition, it is possible that differing disk dissipation timescales for each component could have this effect. In terms of longer term evolution, the components of the binaries with discrepant $v\sin i$'s have spectral types that differ by at most 1.5 spectral subclasses. Thus it is unlikely, given the coevality of these binary components, that the known trend of increasing spindown time with spectral type (or roughly, mass) is the cause of the differing velocities. New simulations of VLM binary formation could shed light on all of these possibilities.

Two of our binary sources (2MASS0746+20AB and LP 349-25AB) are known radio sources (Antonova et al. 2007; Phan-Bao et al. 2007). The components of both of these binaries exhibit rapid rotation (>20 km s^{-1}). This suggests that the rapid rotation helps drive the activity of these sources. Both of these systems also have components with different $v\sin i$'s. This has interesting implications for determining which of the binary components is exhibiting the radio emission, as the radio measurements are typically unresolved. For instance, Berger et al. (2009) used the average $v\sin i$ of the two binary components from unresolved measurements to derive a radius for the radio emitting component, which they assumed to be the primary. However, the secondary is rotating more rapidly and thus is more likely to be the active source. Using the spatially resolved measurement of $v\sin i$ for the secondary rather than the combined measurement gives a different value for the radius, one that is actually consistent with expected values (G. Hallinan et al., in prep). This highlights the importance of obtaining fundamental parameters of binary components individually. Furthermore, it is likely that the secondary component of LP 349-25AB is the radio source, since it is rotating at the extremely rapid rate of ~95 km s^{-1}. This is within a factor of 3 of the breakup speed of this object, and is the most rapid rotator in our sample. Future VLBI observations of both sources will determine conclusively which component is generating the radio emission in these sources. In addition, LP349-25AB would be an excellent candidate for polarimetric observations (i.e., Tata et al. 2009).

With our new measurements, we will be able to compare $v\sin i$ to the masses of these objects. This may shed light on the rotational evolution as a function of mass, rather than spectral type. In addition, these observations can provide an further constraints on the ages of these systems, which in many cases is completely unknown or very uncertain. Age estimates can aid in the comparison of fundamental parameters to evolutionary models. Finally, we aim to obtain $v\sin i$ measurements for a greater sample of VLM binaries and push down to objects with later spectral types, allowing for the characterization of binaries across the entire substellar regime.

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